The Sun-Earth Connection Theory Program (SECTP)

1. Program Description: The Office of Space Science (OSS) established the Sun-Earth Connection (SEC) Theory Program at the recommendation of a pair of studies by the National Academy of Sciences on the state of space plasma physics (including the famous Colgate Report). These studies concluded that "theory needed to play a leading role in the planned development of the field of solar-terrestrial physics". One measure of the success of the SEC Theory Program in meeting the goal set by the Academy is that the next geospace mission in the OSS Roadmap, Magnetospheric Multiscale, has been specifically designed to measure gradients of electric and magnetic fields derived from theoretical considerations. The vision put forth by the Academy panels over two decades ago is even more compelling now. The Theory Program is the most forward-looking of all R&A programs, it defines the observational and measurement objectives that drive the development of the next generation of missions and technology across all SEC.

Of course, theory is essential for the advancement of not only SEC, but all the Themes in NASA's Space Science Enterprise. NASA's mission is "To advance and communicate scientific knowledge and understanding ….", and both the Enterprise and Science objectives of the OSS are to "Understand the … universe, … Solar System, … changing Sun …". The embodiment of scientific understanding is a theory that is rigorously validated by experimental data and observations. Experimentally-validated theories are what go into the textbooks. The role of the Theory Program is to produce such theories from observations and measurements of the present flight program and to propose such theories that will define the future flight program.

From the outset, the SEC Theory Program was carefully crafted to help the OSS achieve its objectives by addressing a key need in the SEC program – theoretical investigations by teams of researchers on major problems that cut across specific missions and help determine the future flight program. The Theory program has two defining features:
All funds are awarded to critical mass investigations. Throughout the two-decade history of the program, awards have been fairly constant at approximately $350K per year. Although this level of funding is usually not sufficient to fully fund typical Theory Program groups of 4 – 5 researchers, it does provide the core support that has enabled these groups to form and to perform their work. Contributing support by awardee institutions has been one of the hallmarks of the SEC Theory Program, and makes it one of the most heavily leveraged of the OSS R&A programs.
All funds are peer-review competed every three years. Open peer-review selection is one of the bedrock principles of the Space Science Enterprise. It has provided the flexibility and turnover essential for the SEC Theory Program to maintain its position at the forefront of SEC science. Due to its competitiveness, the program has always been extremely productive and prestigious, attracting and developing many of the best theory groups in the field, *as judged by the community in open peer-review.*

The Theory Program's focus on critical mass investigations has proved to be the key ingredient for making progress on the Enterprise's objective of understanding the complex interlinked Sun-Earth system. As will be demonstrated in the following sections, a team effort is necessary for developing comprehensive theories of fundamental physical processes such as magnetic reconnection and shock acceleration, and for creating realistic, multi-dimensional models of important phenomena such as coronal mass ejections and geomagnetic storms. The Program's focus on team investigations of fundamental space physics also makes it a perfect complement to the small-scale, individual investigations of the SR&T programs and to the targeted, mission-specific investigations such as GI or Living With a Star (LWS) programs.

Along with its forefront role in SEC science, the Theory Program is also playing an essential role in developing the necessary infrastructure of the SEC Theme. The vitality of a field is completely dependent on its personnel, and the Theory Program has been singularly successful in attracting and developing first-class researchers. Numerous past and present Theory Program groups, including those at Bartol, U. Chicago, Dartmouth, UNH, NRL, SAIC, NCAR and Utah State have obtained permanent positions at their institutions because of the Theory Program. Now that the OSS and the SEC Theme are gearing up to take on major new challenges like LWS, this infrastructure development by the Theory Program will become even more vital.

2. Program Accomplishments: At present, there are 11 groups in the program, distributed across all disciplines of the SEC. The investigations range from the core of the Sun out into the corona, through the solar wind into the Earth's magnetosphere and down to the ionosphere and lower atmosphere. More than any other program, the SEC Theory Program bridges the physical regimes between the different disciplines in SEC and studies the fundamental processes that drives the Sun-Earth system.

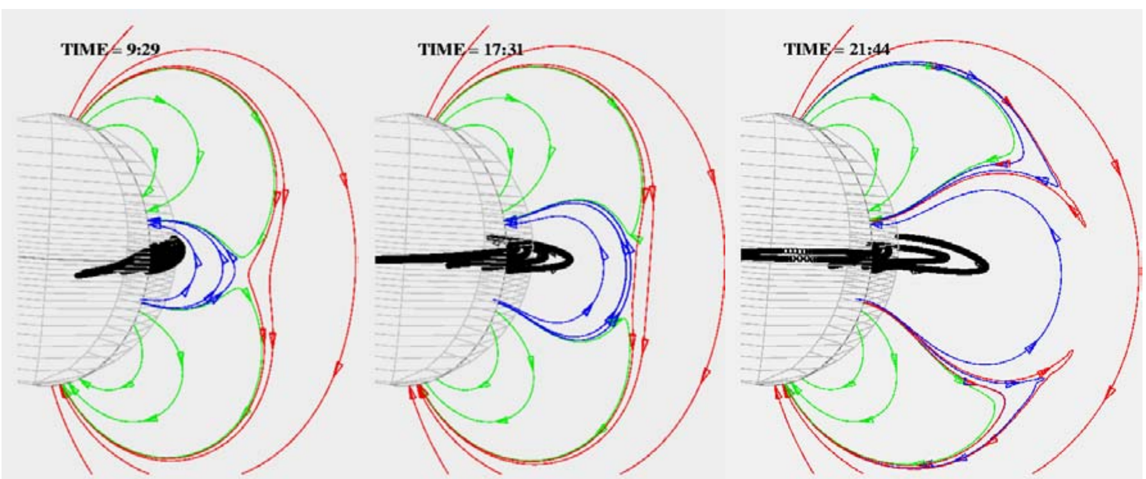
The SEC Theory Program has made many pioneering contributions to NASA science, but perhaps the area that most convincingly demonstrates the unique contributions of the Program, and an area that is becoming increasingly important, is the field of time-dependent multi-dimensional modeling. Models originally developed under the Theory Program are now the workhorses for analyzing space observations and for designing and implementing future missions across all SEC disciplines. In fact, some of the Theory Program models, such as the NCAR/HAO Thermosphere-Ionosphere-Electrodynamics-General-Circulation model (TIE-GCM), the USU Time-Dependent Ionosphere Model (TDIM), and the Rice Convection Model (RCM), have reached such a level of sophistication that they are now considered community resources. The critical mass funding of the Theory Program was essential for SEC theorists to mount the large-scale effort necessary to develop and to apply these models. SEC multi-dimensional modeling capability has also made major contributions to NASA public outreach. For example, the spectacular 3D simulations of the Jan 10, 1997 geomagnetic storm that received extensive public media exposure were due to models originated by the Theory Program.

We describe below recent SECTP results from several of the present teams. These results come in two distinct flavors, investigations of global phenomena, such as the solar wind or the magnetosphere, and investigations of local processes, such as MHD wave acceleration or null-point reconnection. The global studies tend to focus on questions such as: *What are the 3D structure and dynamics of the system? What instabilities lead to those dynamics?* Whereas the local studies focus on questions such as: *What is the mechanism by which magnetic energy is converted to flows or particle acceleration? How fast is energy converted?* The key point we will attempt to emphasize in this proposal is that the future of SEC science, both theory and experiment, lies in the merging of the global and local physics.

3.1 <u>Solar and Heliospheric Dynamics</u>

The SEC science objective of the Enterprise is to "understand our changing Sun and its effects throughout the Solar System". The most important of these effects are due to the Sun's variable emission of plasma and field into the heliosphere. We describe below recent major advances by SEC Theory Program groups in understanding the physics of both the quasi-steady (solar wind) and impulsive (Coronal Mass Ejection - CME) solar outflows.

3.1.1 Explosive ejections: CMEs are giant eruptions of the Sun's plasma and field, ($> 10^{16}$ gm accelerated to > 1000 km/s on a time scale ~ 1000 s). They are the most energetic and most destructive form of solar activity and are, therefore, a core focus of the OSS. They also provide unique opportunities to study global MHD instability/non-equilibrium — processes that are at the heart of space physics and plasma astrophysics. CMEs are generally believed to be a manifestation of the abrupt relaxation of coronal magnetic stress that originated below the photosphere. The outstanding problem in CME physics is to understand their explosive nature. Since the photosphere evolves slowly (< 1 km/s) compared to coronal characteristic response speeds (> 1000 km/s), we would expect the coronal magnetic field to respond to stresses injected from below by simply expanding outward quasi-statically, and in fact, this is exactly the evolution usually observed. Intense theoretical study of the CME problem, both analytical and numerical, has also tended to find only a slow-expansion evolution.



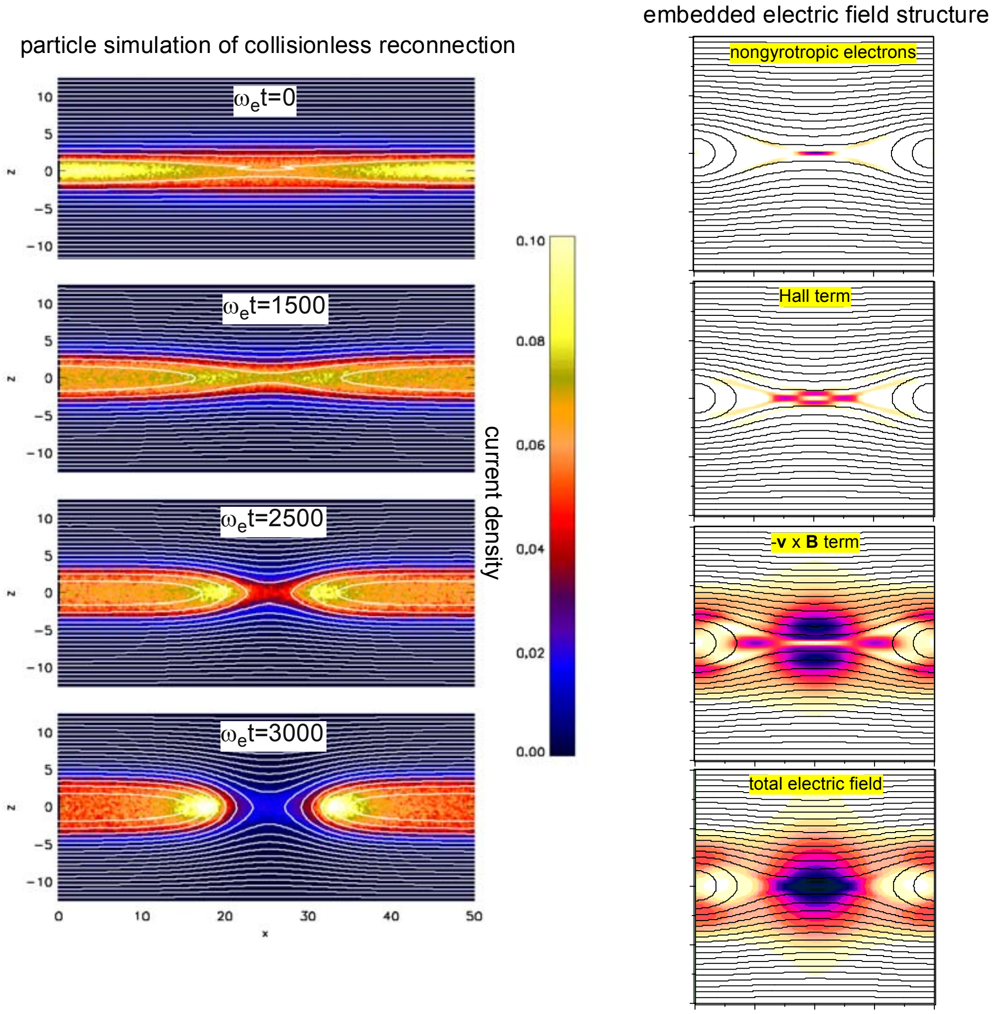
(from Antiochos et al, ApJ, 510, 485, 1999)

Recently the NRL Theory Group has made a breakthrough in understanding the origin of explosive eruptions. The key is to consider not just the highly-stressed magnetic fields that drive expansion, but also the weakly-stressed fields of surrounding regions, which one would normally think of as tending only to inhibit eruption. When the magnetic topology is complex, as is observed for the Sun, magnetic reconnection can indeed produce a catastrophic evolution. Magnetic reconnection is arguably the most important plasma process governing dynamic behavior in space and laboratory plasmas. Broadly speaking, it is a mechanism by which magnetic fields change their topology (field lines "reconnect"), breaking or opening magnetic boundaries. The basic idea behind the NRL model can be seen in the numerical simulation shown above. The thick black lines at the solar equator correspond to newly-emerged field with progressively increasing shear. This high-stress flux tries to expand outward, in order to minimize its energy, but is held back by older overlying flux (blue lines). As the stress increases, however, the restraining field is pushed against oppositely directed high-coronal field (red lines), causing it to reconnect and spring aside, thereby, allowing for more expansion. The key feature of this "breakout" model is that it produces a positive feedback between reconnection and outward expansion. More reconnection removes more blue flux causing a faster outward expansion, but as the field expands outward the current sheet separating the blue and red flux becomes thinner and longer, producing a greater rate of reconnection. This feedback between driver and response is the physical basis of exponential growth. It should be noted that although the configuration above is specific to the CME problem, the basic mechanism appears to be quite general, and may be applicable to other dynamic cosmic phenomena of interest to the OSS. Another key feature of this model is that in order for the reconnection rate to keep up with the outward expansion, very thin current sheets must form, at scales down to meters. Hence, the evolution of a system of giant size like the Sun's corona, can be governed by the physics of a region with sizes typical of our everyday experience. This highly intriguing result points out the importance of understanding feedback between scales.

3.1.2 Magnetic Reconnection: In order to achieve NASA's science goals, we must understand magnetic reconnection, because this process is the heart of the Sun-Earth connection. Space weather, in general, can be thought of as simply a chain of reconnections, beginning with energy release at the Sun by reconnection in the corona, then coupling to Earth's magnetosphere via reconnection at the magnetopause, and finally dissipation in the ionosphere by reconnection at the magneto-tail. The central question regarding reconnection has been whether the rate is "slow" in that it is sensitive to plasma resistivity (Sweet-Parker model), or "fast" – almost independent of resistivity (Petschek model). A debate has raged in the literature for decades over which of these two models gives the correct picture. This question obviously has enormous implications for understanding explosive phenomena throughout the cosmos.

Recent work by a number of groups, including the SEC Theory Program group at LANL/GSFC/UMD, appears to have finally resolved the issue of the reconnection rate. The key was to include collisionless effects. In laboratory plasmas magnetic reconnection is usually enabled by collisions between charged particles, which decouple the particles from the magnetic field. Particle collisions, however, are ineffective for most space plasmas, so that any fast reconnection must be due to collisionless processes. Theory Program supported research led to a breakthrough in understanding collisionless reconnection. The main factor in achieving this improved understanding was the application of various (similar as well as dissimilar) simulation codes to a problem of reconnection. This involved a collaborative effort by several groups including the LANL/GSFC/UMD Theory Program group. Note that in this case, major progress in understanding required a critical mass larger than even that of a Theory Program group. The insight came specifically from the fact that when a number of different simulation codes were applied to the same problem, they discovered a three-zonal structure for the reconnection site (figure below) with different physics dominating each of the zones. The left column in the following figure shows the magnetic field and current obtained from one of the LANL simulations and the right column demonstrates the embedded zones. In the outermost "global" zone, both ions and electrons are tied to the magnetic field through their gyro motions, supporting a standard fluid-like description. Next is a region in which electrons are tied to the magnetic field but ions are free. The innermost zone is governed by non-gyrotropic electrons, which act to produce a large effective resistivity and, hence, fast reconnection. But, despite the crucial role of electrons in the dissipation, the reconnection time scale is governed by ion motions, in agreement with standard theory.

(from Hesse et al., Phys. Plasmas, 6, 1781, 1999)



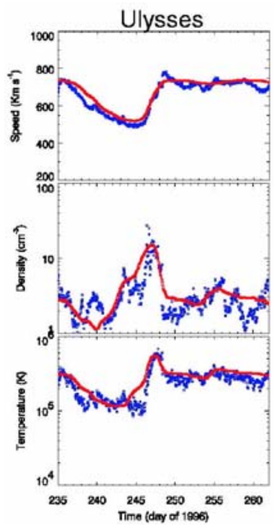
Now that progress has been made in understanding the basic physics of reconnection, major questions such as, *what are the conditions that lead to the transition from a relatively stable configuration to the onset of reconnection?* can be tackled. Due to the contributions of the Theory Program, the OSS is now ready to make deep advances in our understanding of this most fascinating of space plasma processes, and to address the challenge of coupling this understanding to the global modeling.

3.1.3 The Solar Wind: One of the most famous triumphs of NASA's space science program was the direct measurement by Mariner 2 of the solar wind, first predicted on theoretical arguments. Parker's solar wind work is perhaps the most striking example of how theory inspired the NASA science that revolutionized our view of the cosmos. Furthermore, NASA missions and science investigations have shown that the vast majority of other stars have winds and coronae, hence, advances on understanding the Sun's wind have broad applicability throughout the OSS.

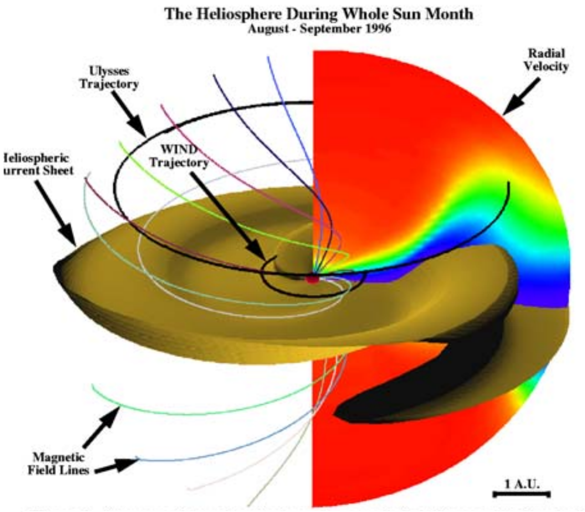
Since its discovery, we have also learned that the solar wind has an importance well beyond space science. The continual outflow of solar plasma and field into the heliosphere constitutes the fundamental medium of our space environment and carries the effects of activity, such as the CMEs described above, to the Earth and other planets, creating much of the Sun-Earth Connection. Consequently, understanding the generation, structure and dynamics of the solar wind, a field pioneered by NASA, is a principal objective of the OSS.

SEC Theory groups have recently made great progress in solving two fundamental problems in solar wind physics: determining the mechanism for the acceleration of the wind, and determining how the complex plasma and field structures in the corona are connected to the structure of the outer heliosphere. The figures below show the results of the most comprehensive model to date of the solar corona-heliosphere system. The model is fully 3D and extends from the surface of the Sun to well beyond Earth's orbit, out to 5 AU. It required man-years of work by the Theory Program team at SAIC. Their model uses the observed line-of-sight magnetic field at the photosphere as boundary conditions, and solves the fully time-dependent MHD equations, including a sophisticated treatment of energy transport with thermal conduction and optically-thin radiation, in order to determine plasma properties and magnetic fields throughout the heliosphere. The figures below present results of simulations of the solar wind during "Whole Sun Month", Aug. – Sep., 1996, which occurred shortly after the minimum of solar cycle 22. This time period is particularly favorable for modeling because of the availability of many coordinated data sets, and because the magnetic structure of the Sun is usually less complicated during minimum. The panel on the right shows the radial velocity of the plasma as well as the regions of strong electric currents, which coincide with the surface where the magnetic field changes direction. Note the field lines that extend from "coronal hole" regions near the Sun's poles out to 5 AU. With this model we can connect quantitatively the structure of the far wind to its solar origins. Also plotted on the right are the trajectories of two spacecraft, WIND and Ulysses, which obtain in situ measurements of the plasma. The model does an excellent job at reproducing the solar wind velocity and temperature, but further research is clearly needed in order to understand the observed density variations (left panel). The SAIC model opens up the exciting possibility of being able to determine the solar wind structure from observations of the solar surface, even during times of high-activity when the Sun's field is much more complex and dynamic. An enhanced version of this model is planned to be the workhorse for achieving the science goals of the next SEC mission, STEREO, which will obtain multi-point *in situ* measurements of the wind simultaneous with 3D coronal observations.

A key point is that, just like the global CME model discussed above, the SAIC global solar wind model is not completely self-consistent because it uses an assumed functional form for the wind acceleration, which is almost certainly due to local processes. The mechanism for accelerating the solar wind is not fully understood yet, and is one of the core problems in space science. Parker's seminal work showed that a wind is the inevitable outcome of the thermal expansion of a hot 10^6 K corona. NASA missions discovered, however, that the basic state of the wind originating from large open field regions (coronal holes) is the fast wind (V ~ 800 km/s), and theoretical work has shown that the fast wind requires acceleration additional to that of a thermally-driven wind. Based on both theoretical and observational results, we now believe that the generation of a fast wind requires substantial heating low in the corona, well below one solar radius, and direct momentum deposition high up, above several radii. This conclusion strongly suggests that the heating and acceleration are due to Alfven waves, because only such waves are likely to carry the required energy on the open magnetic field lines of coronal holes.



Comparison between Ulysses spacecraft measurements (blue) and 3D MHD simulations (red) during the Whole Sun Month Interval.



Structure of the solar wind speed, magnetic field lines, and heliospheric current current sheet in the inner heliosphere during the Whole Sun Month time period.

(from Riley et al, JGR, 2001, in press)

Theory Program groups at UNH and Bartol have been at the forefront of research on wave heating and acceleration of the Sun's wind. The main difficulty for wave heating models is that observed photospheric motions, the ultimate power source, are expected to produce Alfven waves with spatial scales too large and frequencies too low for the waves to damp in the low corona where the heating is needed. Hence, theoretical work has focused on determining mechanisms that can transfer the input power to small scales and/or high frequencies where efficient damping processes are known to operate. Turbulence is a general physical phenomenon that does exactly this — turbulence cascades input power down to scales where it can dissipate. Recently, the Bartol group has drawn on their extensive work in MHD turbulence theory to develop a model that produces power at small scales. The interesting new feature of the model is that partial reflection of upwards propagating waves creates a region in the low corona of "colliding" oppositely directed waves, and their nonlinear interaction leads to a turbulent cascade. The Bartol model makes the important prediction that the heating varies exponentially with altitude, a result that TRACE has recently observed in closed field regions. Future missions need to be designed to test this prediction in open regions, where the wind originates.

The UNH Theory Program group, on the other hand, has focused on mechanisms that transfer power to high frequencies (ion-cyclotron waves), where it can dissipate efficiently by wave-particle interactions that occur when the wave frequency becomes resonant with the particle's frequency of gyration about the magnetic field. The UNH group essentially founded the field of ion-cyclotron wave theory. They developed the basic formalism, performed the pioneering calculations, and made detailed predictions of the heating rate for different ion species. A key point of the theory is that particles with lower gyrofrequencies, such as heavy ions, will be heated preferentially because there is more wave power for them to resonate with. Consequently, the UNH group made the bold prediction, that heavy ions in coronal hole regions would be orders of magnitude hotter than the bulk protons, a prediction that at the time was considered too radical to pursue. But, in fact, their prediction was recently confirmed by the UVCS spectrometer on SOHO, an observation that is widely regarded as one of SOHO's great discoveries and that has generated considerable public press for NASA. This work by the UNH group, which required a dedicated team effort possible only through the Theory Program, must be regarded as a major achievement of the OSS science program. Of course, a great deal of work remains to be done, both on understanding the processes for the wave generation and dissipation, and on coupling our theories for these local processes to the global models in order to achieve a truly self-consistent model for our Sun's wind.

3.2 GeoSpace Structure and Dynamics

As the solar wind flows past the Earth, it encounters the Earth's strong magnetic field, which deflects the bulk of the solar wind around the Earth. The net result is that a large, comet-shaped, magnetic cavity is formed, called the magnetosphere. The head of the comet-shaped region occurs on the sunward side of the Earth, where the solar wind's dynamic pressure acts to compress the geomagnetic field, while the solar wind flow past the Earth acts to produce an elongated tail on the nightside that extends well past the Moon's orbit. Inside this vast volume are large-scale current systems, magnetic and electric fields, and both thermal and energetic particles, including the Van Allen radiation belt. When there is a sudden increase in the dynamic pressure of the solar wind, which occurs when the Earth is impacted by coronal mass ejections or solar flare material, geomagnetic storms and substorms can be triggered. The sudden increase in the solar wind's pressure results in a reconfiguration of the magnetosphere as well as enhancements in the electric fields, particle precipitation, and field-aligned currents that link the magnetosphere to the underlying ionosphere-thermosphere system. Although the linkage is primarily in the Earth's polar regions, the storm induced enhancements in the particle and electric field heating rates are sufficient to affect the density, composition, and circulation in the ionosphere-thermosphere system on a global scale, and the modifications can persist for several days after the geomagnetic storm subsides.

3.2.1 Geomagnetic Storms: Storms and substorms can have a significant impact on human systems and operations. They can affect HF communications, over-the-horizon (OTH) radars, surveying and navigation systems that use Global Positioning System (GPS) satellites, surveillance, satellite tracking and lifetimes, electrical power grids, and pipelines. Because of their effects, it is not surprising that one of the primary focuses of the SEC Theory Program is to elucidate the basic physics associated with the triggering and evolution of geomagnetic storms and substorms. However, because geomagnetic storms and substorms produce world-wide effects and involve the magnetosphere, ionosphere, and thermosphere, global models are needed to trace the flow of mass, momentum, and energy both within a domain and from one domain to another.

The comprehensive global models that are required were developed with the critical mass funding provided by the SEC Theory Program, and they are now being used to study geomagnetic storms and substorms. The group at Boston University is using a sophisticated, global, magnetohydrodynamic (fluid-like) model of the outer magnetosphere to calculate the flow directions, and the electric and magnetic field configurations, during geomagnetic storms. The group at Rice University is using a state-of-the-art kinetic model of the inner magnetosphere to study the energetic particle dynamics and precipitation characteristics associated with geomagnetic storms and substorms. The Utah State University group is using a global model of the coupled ionosphere-thermosphere-polar wind system to conduct high-resolution studies of this system's response to geomagnetic storms and its feedback on the magnetosphere. In addition, the NCAR group is using a coupled model of the ionosphere-thermosphere-mesosphere system to study the propagation of storm energy from high to low latitudes and from high (the thermosphere) to low (the mesosphere) altitudes. During the last five years, these complementary studies have resulted in a significant increase in our understanding of the dynamics and energetics of storms and substorms. Some of the effects that geomagnetic storms have on the thermosphere-ionosphere-polar wind system are highlighted in what follows.

During a geomagnetic storm, the enhanced electric fields that are generated by the solar wind-magnetosphere interaction are mapped down along the Earth's magnetic field lines and induce a large-scale motion of the ionosphere in both the northern and southern polar regions. This motion, which is primarily parallel to the Earth's surface, has a significant effect on the electron density morphology. In addition, as the ionosphere drifts through the neutrals at speeds as high as 4 km/s, the ion and neutral temperatures are elevated due to ion-neutral frictional heating, which modifies the chemical reaction rates, ion velocity distributions, and ion composition. In the auroral oval, the storm-enhanced particle precipitation acts to increase the electron densities at low altitudes and the electron temperatures at all ionospheric altitudes. The increases in the electron and ion temperatures then induce a large-scale upflow of plasma in the polar regions, which is called the polar wind. In response to both the changes in the ionosphere and the storm energy input, equatorward propagating gravity waves are excited in the neutral upper atmosphere. Behind the gravity waves are enhanced horizontal neutral winds, neutral gas upwelling, and O/N_2 composition changes.

Global numerical simulations of the effects that geomagnetic storms have on the thermosphere-ionosphere-polar wind system have recently been conducted by the USU and NCAR Theory Groups. Figure 3.2.1 shows snapshots of the neutral temperature and wind fields at 120 km both before and during a geomagnetic storm. The elevated neutral temperatures and enhanced upper atmospheric winds are clearly evident during the storm, as is their global nature. Associated with the elevated neutral temperatures are neutral gas upwellings and increased N_2 densities near the peak of the ionosphere. The increased N_2 densities, coupled with the increased $O^+ + N_2 \rightarrow NO^+ + N$ reaction rate due to elevated ion temperatures, act to significantly modify the ion composition in the polar ionosphere, as shown in Figure 3.2.2. During a storm, the dominant ion at and below the ionospheric peak can change from O^+ to NO^+. In addition to the chemical destruction of O^+, the O^+ density at the peak altitude is further reduced due to the large-scale upflow of O^+ in response to the storm-enhanced electron and ion temperatures. Figure 3.2.3 shows a snapshot of the storm-time O^+ density as a function of altitude and latitude (along the noon-midnight meridian). During the storm, the O^+ density is sufficiently elevated that O^+ becomes the dominant ion to altitudes as high as 9000 km over the bulk of the polar regions. Also, the escaping O^+ ions are an appreciable source of mass and momentum for the magnetosphere, and their presence affects the recovery phase of a geomagnetic storm. Finally, the simulations indicate that during the storm the temporal variation of the plasma density at high altitudes (~9000 km) can be opposite to that at low altitudes (~300 km), which makes it difficult, if not impossible, to elucidate storm dynamics with just one satellite (clusters of satellites are needed).

The global simulations have clearly established that the processes acting within and on the magnetosphere-ionosphere-thermosphere system occur at different locations and different times. Therefore, global models are needed to relate past events that occur in adjacent regions to the in situ measurements made along satellite orbits and to the remote sensing scan planes. Also, since the processes operate over widely different spatial and temporal scales, models are needed to integrate the effects so that they can be related to line-of-sight (column integrated) satellite measurements. The need of global models will grow in the coming years because NASA's future spacecraft programs will be based primarily on satellite constellations and remote sensing. However, the global numerical models do not include mesoscale and small-scale (instability)

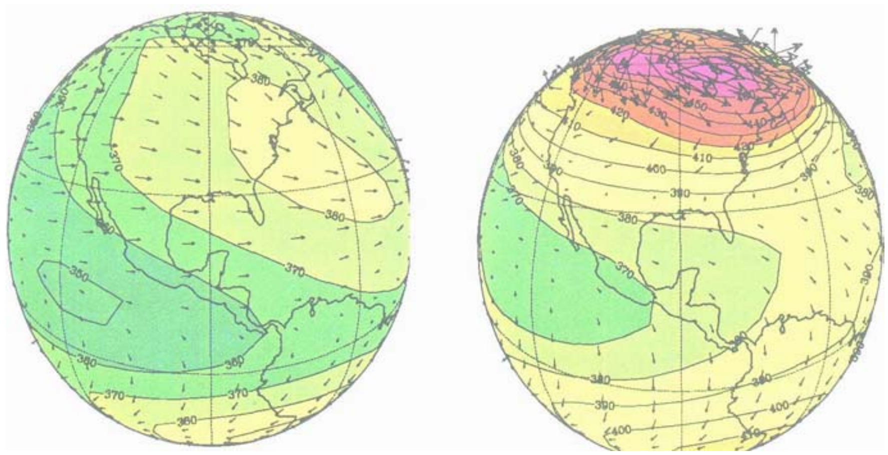


Figure 3.2.1. Global distributions of temperatures and winds in the Earth's upper atmosphere at 120 km. The left panel is for quiet conditions and the right panel for storm conditions. The pink color shows the region of substantially elevated neutral temperatures. **(from Roble, AGU Monograph 123, 53, 2000)**

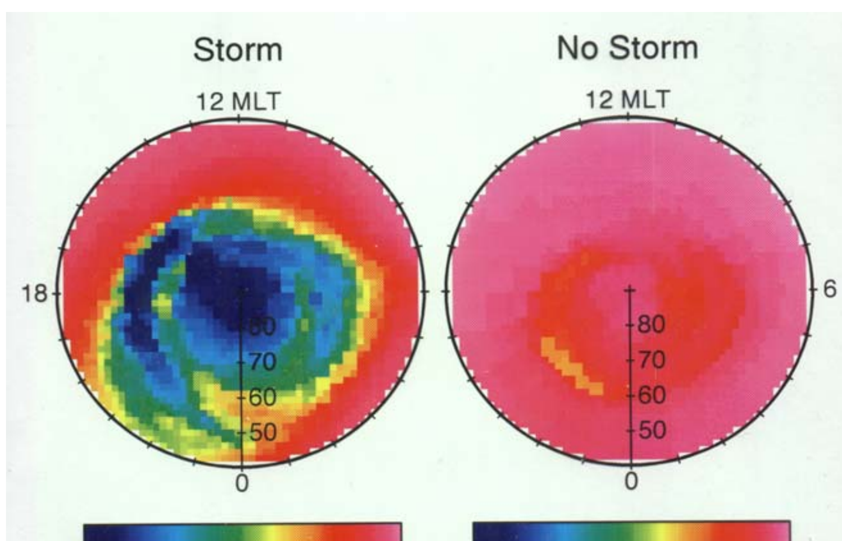


Figure 3.2.2. Distributions of the O^+/N_e ratio at 300 km in the northern polar region for storm (left panel) and quiet (right panel) conditions. A magnetic latitude – MLT coordinate system is used. Pink means O^+ is the dominant ion and blue means NO^+ dominates. **(from Schunk, AGU Monograph, 109, 195, 1999)**

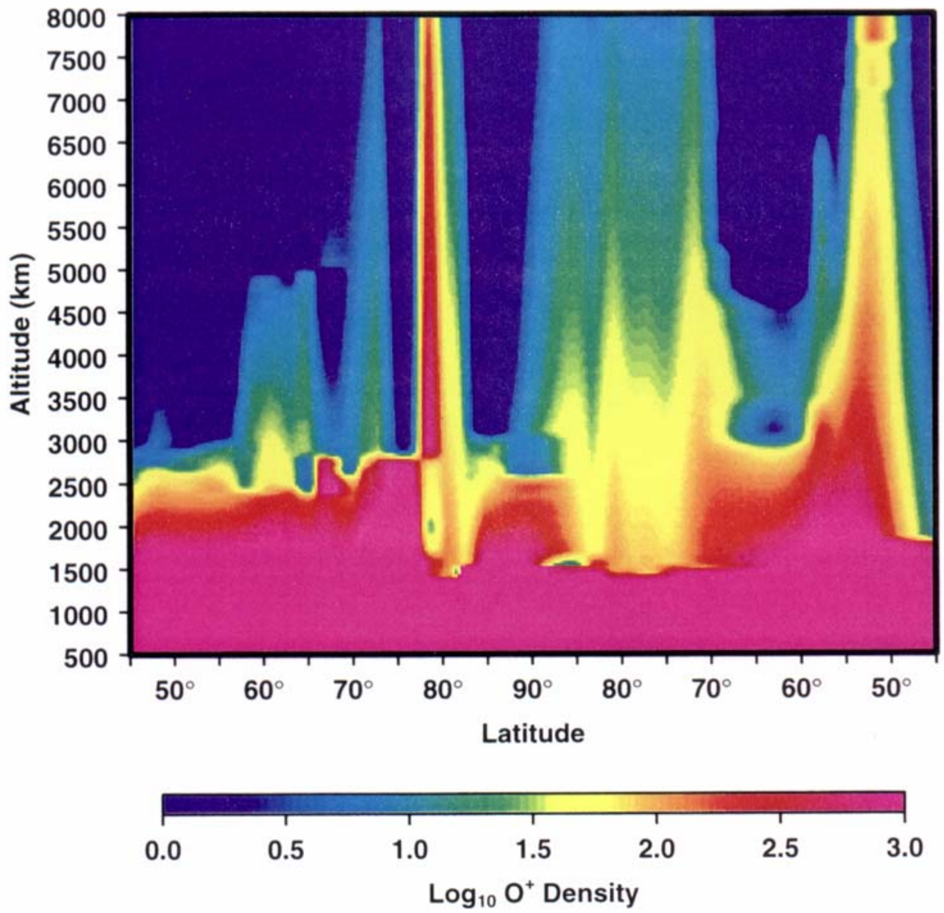


Figure 3.2.3. Shapshot of the O^+ density distribution as a function of altitude and latitude during a geomagnetic storm. The latitude range is from 50° on the dayside to 50°on the nightside along the noon-midnight meridian. Densities greater than 10^3 cm^{-3} are colored pink and those below 10^0 cm^{-3} are dark blue. The snapshot is for 6 UT, winter, and solar maximum conditions in the northern hemisphere. **(from Schunk, AGU Monograph, 109, 195, 1999)**

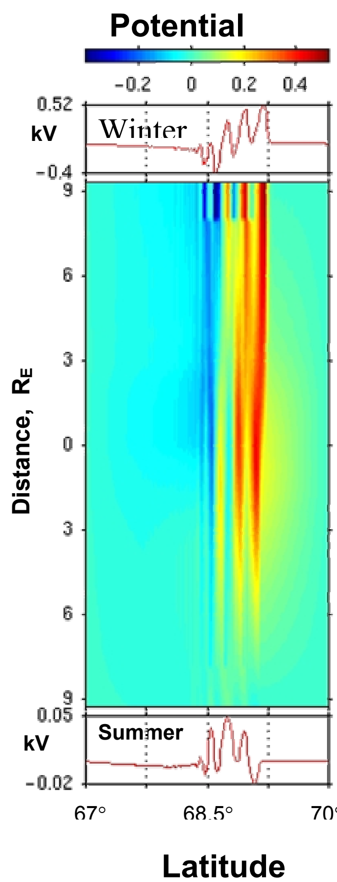
processes, and yet these processes may play an important role in the momentum and energy exchange between different regions. Typically, the mesoscale and small-scale processes are modeled only in a localized region, and their effects on the global dynamics and energetics are ignored. This is because the numerical models needed to describe such processes may require spatial steps as small as centimeters and time steps as small as nanoseconds, depending on the problem.

3.2.2 Auroral Displays: The fact that mesoscale and small-scale processes are effective in transferring energy from one geospace domain to another can be clearly established just by looking at auroral displays (below left). The discrete auroral arcs are a result of energetic electron precipitation in narrow latitudinal channels (1-100 km wide). These arcs often appear as multi-banded structures that intensify, drift north or south, and then fade. The energy deposited into the Earth's upper atmosphere by the precipitating electrons in discrete arcs is significant, but this energy is not included in global models of the magnetosphere, ionosphere, or thermosphere.

The reason why discrete arcs are not included is that they are at the sub-grid level of the current global models. However, a localized model of discrete arcs that captures all of the essential physics has recently been developed by the Dartmouth Theory Group.

The Dartmouth scientists have captured the physics of discrete arcs by coupling a model of ionospheric dynamics to a model that describes the low-frequency electrodynamics of a magnetic flux tube connecting the northern and southern ionosphere. This model, which takes account of small spatial and temporal scales, has shown that electromagnetic waves are generated, and then propagate along geomagnetic field lines, whenever there are changes in the ionosphere or magnetosphere. There are field-aligned currents associated with the electromagnetic waves, and when microturbulence develops in the current system, discrete arcs form. The microturbulence produces an electric field that is parallel to the geomagnetic field at an altitude of about 6000 km (below right), and this electric field (parallel potential drop) accelerates the precipitating electrons, thereby creating the discrete auroral arc. Many aspects of the model, including the strength of the parallel electric field, magnitude of the field-aligned current, and the energy of the precipitation, have been verified by comparison with data from the FAST satellite.

Multibanded, north-south drifting discrete arcs are frequently observed from the ground **(photograph by Jan Curtis)**



Field-aligned potential drop between winter and summer ionosphere versus inter-hemispherical distance and magnetic latitude.

(from Pokhotelov et al., Trans. AGU, 81, F1018, 2000)

4. Conclusions and Recommendations:

We stress that the results described above are only a sample of recent progress made by Theory Program groups. Whole areas with exciting new advances, such as studies of the solar interior and the Earth's radiation, belts could not be included due solely to space limitations. Even this small sample, however, demonstrates that the Theory Program has more than met the goal set by the National Academy and the requirements set by the OSS strategic plan. All the SEC missions presently under development have had critical input from the Theory Program. For example, spectroscopy was added to the mission complement of SOLAR-B specifically for the purpose of detecting the magnetic reconnection predicted by theoretical models such as that in Section 3.1. The whole concept of the STEREO mission stems from consideration of 3D models for CMEs and the solar wind, such as in 3.1. MMS is being designed on the basis of reconnection in the magnetosphere as described in 3.2. The soon to be launched TIMED mission was designed to address the neutral and ion dynamics in the lower thermosphere that were predicted by the 3D models discussed in 3.2. Due to its pioneering of large-scale modeling, the Theory Program has laid the scientific foundation for, and is playing a vital role in, development of the LWS program.

Of course, the theories that are driving SEC missions and technology are certainly not due only to the Theory Program. Theory is a community endeavor that requires the involvement of all OSS programs, but the SEC Theory Program has clearly made unique and essential contributions because of its focus on critical mass groups. The type of results presented in the previous section would not have been possible for an individual researcher. Furthermore, the need for critical mass theory is only increasing. Space physics is a field with theory needs several generations beyond the "order-of-magnitude-model" stage, and experimental needs well beyond the "discovery" mode. For example, many of the SEC missions planned for the coming decade will involve several spacecraft, and for some missions, perhaps, as many as dozens of satellites. Such missions will deliver truly 3D data sets. Defining the instruments, and interpreting and incorporating their data into theoretical models will require a next generation modeling that only critical mass groups will be able to deliver.

In addition to its increasingly important responsibility of directly enabling SEC missions, the Theory Program is now facing a major new challenge, but a challenge that is also an exciting new opportunity. We are now poised to attack the fundamental problem of the interaction between global and local physical scales. As evident from the previous sections, a key property of the Sun-Earth physical system and of space plasmas, in general, is that their dynamics are often determined by feedback between scales. A phenomenon like a CME or a geomagnetic storm is clearly global, yet its behavior depends critically on the physics of a small-scale reconnection region. However, the evolution of the reconnection region, itself, will depend on the evolution of the global driver. This property of "scale feedback" is found throughout the SEC, and is perhaps the most difficult and most profound problem in space physics. It is also perhaps the most important, because scale feedback invariably plays the determining role in the coupling of neighboring global systems. Space plasmas rarely exhibit a smooth transition from one domain to the next, preferring instead to develop a thin interface with extreme complexity and dynamics, and often with different physics than the global domains. An obvious example is the interface between the solar wind and magnetosphere, another is the solar convection region and the corona. In both cases the interface region formed by the interaction of the global domains develops spatial and temporal scales and has physical properties strikingly different than those of the global regions. But the global structure and evolution is, in turn, strongly affected by processes at the interface.

If we are ever to achieve NASA's and the OSS's objective of understanding the Sun-Earth system and its linkages, we will need to develop rigorous theories and models for scale feedback. At present, local physics is usually incorporated into global models as paramaterized transport coefficients, while the global physics is incorporated into local models as prescribed boundary conditions. We must treat the two regimes with a unified self-consistent approach. This will be a major scientific challenge requiring the development of new types of theories and computational tools. But now is the appropriate time to explore this exciting frontier. We have developed working theories for phenomena such as CMEs, the solar wind, and geomagnetic storms, along with fully 3D global models. We have achieved a deep understanding of local processes such as reconnection and MHD wave dissipation. Furthermore, powerful new computational methods such as adaptive mesh refinement and embedded grids are coming on line. We also expect to obtain from upcoming ST Probe and LWS missions coordinated global and local observations that will help inspire and test new theories. The Theory Program is now ready to take up the challenge and the opportunity of understanding scale feedback in space plasmas.

In order to meet this challenge successfully, however, the Theory Program must have additional resources. The present budget level for the program is far too small to allow the Program to take on a new initiative and, indeed, threatens its continued success. Funding per group has been level for many years, and as a consequence, inflation has eroded the personnel support per grant. This is of particular concern to us, because it jeopardizes the critical mass feature that has been so essential to the Program's success. Furthermore, the decrease in personnel support has been compounded by the recent arrival of vast amounts of excellent new data from the highly successful SEC flight program. The Theory Program resources are now stretched so thin that the effective use of these vast data sets for model development and validation is being compromised.

We propose, therefore, that the OSS increase the Program's funding level in order to achieve the following two goals. **(1)** Increase the funding per group from the present \$350K per year to \$450K so that the groups selected will have the critical mass necessary to address major problems. **(2)** Start a new initiative directed at understanding scale feedback in solar system plasmas so that the Theory Program will be able to mount a comprehensive, multi-team attack at this vitally important, but challenging problem. This initiative will require four to five additional, closely-interacting groups. Since the problem of scale feedback is so ubiquitous and so important throughout space plasmas, at least this many groups will be needed in order to cover all the major SEC domains and their interfaces. This new initiative will help ensure that the Theory Program maintains its very forward-looking role that is so necessary for the future of the SEC. If successful, the results of the scale-feedback initiative will enable SEC researchers to construct truly self-consistent "first-principles" models for phenomena such as CMEs, the solar wind, and geomagnetic storms. This would be a major triumph for the OSS science program and would go a long way towards fulfilling NASA's objective of understanding the universe and solar system.